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Procedia CIRP 36 (2015) 159 – 164

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CIRP 25th Design Conference Innovative Product Creation

Design and inspection of multi-fixturing pallets for mixed part types

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Abstract

Over the last decades, manufacturing market has been characterized by small batch size, high variability in the part types and part type demand, continuous evolution of the products. In order to quickly answer the new and changing production requirements, the rapid redesign of the pallet in terms of number of parts and part types and the verification of physical mounted pallet became essential. Thus, this paper aims at (i) developing a dynamic process planning approach automatically providing multi-part pallet designs and (ii) identifying flexible techniques for the inspection of the physical pallet before its machining. Specifically, the approach analyzes the solution space generated by all the possible combination of part type setups in terms of number and position on the pallet. The number of produced part types per pallet is maximized, while the setup accessibility and an equal number of part types for each setup are granted. The 3D design of the pallet is compared with the scanned pallet cloud of points in order to identify possible error sources, e.g. part missing, incorrectly closed fixture, part type in wrong position. A test case will be provided in order to show the advantages deriving from the approach employment.

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation

Keywords: Keywords: Process planning, Multi-fixturing pallet, Pallet inspection

1. Introduction

Process planning efficiency and effectiveness is more relevant as long as the market is characterized by high product variability in terms of part types and demand fluctuations [1]. In such a dynamic environment, the majority of the parts are characterized by reduced life cycle requiring small production batches. This makes advantageous the employment of dynamic process planning and Network Part Program (NPP) techniques [2], with particular reference to the design and inspection activities for multi-fixturing pallets. On the one hand, the continuous reconfiguration of the pallet in terms of part mix and quantity can increase the capability of the system to answer an unforeseen fluctuation of the demand and a rapid evolution of the products. For instance, when the workpiece setups to be machined are known, their disposition on the pallet could be optimized by maximizing the number of finished part per pallet and granting the same number of part for each part setup. On the other hand, a high variability in pallet designs could lead to errors during the pallet mounting in terms of incorrectly closed fixtures, incorrect mounted part type, unmounted workpiece etc. Thus, a rapid and efficient pallet inspection could increase the system flexibility at the shop-floor level and the exploitation of NPP advantages.

In this paper, the Network Part Program approach is extended through the proposition of a new model for pallet design considering multi-part types and the development of a pallet inspection procedure. The paper is structured as follows: Section 2 presents the literary overview; Section 3 discusses the approach and its innovative aspects in comparison to the existent approaches; Section 4 and 5 are respectively dedicated to the description of the pallet design and inspection approach; in Section 6, results on an industrial test case are presented and discussed; finally, Section 7 presents conclusions and future work.

Peer-review under responsibility of the scientific committee of the CIRP 25th Design Conference Innovative Product Creation
doi:10.1016/j.procir.2015.01.007

2. Literary review

2.1. Process planning

Dynamic process planning [3] and Newtork Part Program [2] are traditionally structured in four main steps. The *first step* concerns the workpiece (WP) analysis aiming at the identification of the workpiece operations. When the approach is compliant to the STEP-NC standard [4], the workpiece is described in terms of machining feature, machining operation and machining workingstep (MWS), that are respectively the description of a workpiece machined region, the technological information and manufacturing strategy for the machining of a feature and the associations between a feature and an operation.

Based on these operations, the setups for the complete machining of the part are defined (*second step*). The setup planning problem determines the number of orientations of the workpiece in the 3D space to be completely machined. The orientation of the workpiece influences the accessibility to its operations, i.e. the visibility of the operation tool access direction (TAD). Each change in the orientation of the workpiece requires an un-mounting and re-mounting of the workpieces on the fixture, and consequently a certain time utilization and the risk of compromising the machining precision and manufacturing quality.

In case of a manufacturing system exploiting the adoption of pallets, the *third step* concerns the pallet design that is the identification of the number and position of workpieces on the pallet so that the operation and setup accessibility are granted [2]. The pallet design problem aims at determining the number, disposition (pattern) and mix of pieces to be clamped on the fixturing device of the pallet as well as part positions. Once the number of the machine tool axes is selected, the accessibility to the workpiece MWSs depends on both setups and pattern.

The *forth and last step* deals with the generation of the program of the pallet according to the standard ISO 6938 (1982) [5]. During G&M-code generation, several factors have to be considered: (i) the machine tools the pallet is going to visit, (ii) the execution sequence of the pallet operations [6], (iii) possible difference between the designed pallet and the real pallet in terms of mounted parts, tolerances due to the fixturing systems, etc. Literary review in relation to pallet design and inspection is given in the followings.

2.2. Pallet design

In [7], a setup planning and a pallet design approach minimizing the number of workpiece setup for the machining on three-, four- and five-axis machine tools is proposed. This approach is extended in [8], while granting the compliance to the STEP-NC standard [4]. A further extension towards sustainable manufacturing can be found in [2] where a mathematical model is proposed for the identification of setup planning and pallet configurations that minimize the energy consumption. However, all these approaches are limited in the number of part types that can be mounted and the number of workpiece setups that a pallet physical face can mount: the approaches consider a single part type under the hypothesis that each physical face can host several workpieces all in the same setup.

On the contrary, [9] proposes a four-step methodology for the machining of different part-types on the same pallet. Even if it copes with workpiece grouping and allocation of workpieces on the pallet, problem related to the saturation and balancing of the pallet are not considered.

2.3. Pallet inspection

The problem of pallet inspection refers to the more general of comparing real objects with ideal geometry, which has been largely studied in literature mainly for precision and quality control of produced parts and, more recently, to improve tool path planning [10]. This process is based on the measuring and the checking of the pallet: first, the measurement of the physical pallet has to be obtained; second, this measurement has to be compared with a reference pallet data for validation. On the one hand, little scientific work dealing with methods for the automatic inspection of the pallet can be found. On the other hand, industrial practice traditionally adopts low-technological methodologies.

The *measurement* of the real parts, e.g. the pallet, can be done by using contact or contactless systems, such as coordinate measuring machines (MCC) or laser/optical scanners. Contact devices are the most common in the industrial practice, even though they present several intuitive limitations, such as low reconfigurability level and customization accordingly to the object to be measured, high costs and time. With particular reference to vision systems, these limitations make contactless technologies more adequate in terms of both profitability and efficacy to the employment in dynamic environments such as Flexible Manufacturing Systems (FMS).

The *comparison* between the acquired data and the related ideal representation requires two main steps: (i) registration of the two models in a reference system; (ii) effective comparison.

Different inspection commercial systems exist, but they are not usable for the fully automatic detection of deviation as requested in Flexible Machining System monitoring, since most of them require manual intervention for the registration process. [11] and [12] present a comprehensive literature review of the main issues, methods and processes related to part inspection. Methods may differ for the common used representation: various works transform CAD data into polygonal meshes [13], while others convert acquired points to B-splines of NURBs [14]. The registration is generally provided in two consecutive steps: rough and fine localisation. Among the various methods for fine alignment, the Iterative Closest Point is the most used [15,16]. To improve efficiency, rough localisation may use only a limited number of measurement points for coordinate system alignment, possibly based on some feature detection [14,17].

For the effective difference calculation between the acquired and ideal surface, two methods have been mainly applied: computing the plane point distance or directly computing the point-to-to-point distance between closest point pairs/corresponding points between two surfaces [12].

3. Approach

The goal of this paper is to propose an extension of existent dynamic process planning approaches relaxing some hypothesis at the basis of pallet design models and introducing pallet inspection as a necessary step for the part program generation. The new schema for process planning is presented in Fig. 1.

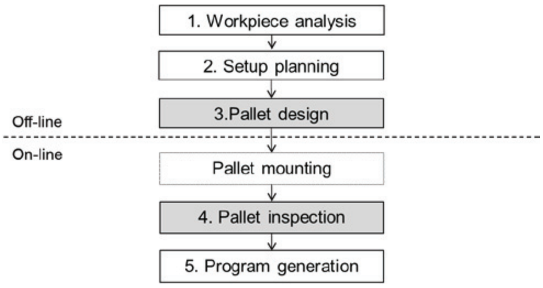

Fig. 1. Process planning approach

The first goal is to definition of a new model able to quickly provide alternative pallet designs (Step 3) in order to be able to answer a continuously evolving demand. The model takes into account the mounting of different part types and different setups on the same physical face of the pallet; pallet saturation and balancing. The machinability of the pallet on a predefined set of machine tools is also addressed.

The second goal is to introduce in the process planning the inspection step (Step 4). The idea is to select the necessary hardware and to develop the required software in order to quickly obtain a 3D image of the mounted physical pallet. This image compared to the 3D image generated during the pallet design will allow the identification of possible errors in the pallet mounting and the adjustment of the part programs.

Pallet design and inspection approaches are described hereafter. Workpiece analysis and setup planning methodologies are derived from [2].

4. Pallet design

The goal is to develop a methodology able (i) to quickly provide alternative pallet designs given a set of workpieces, workpice setups, pallets and (ii) to asses to pallet machinability on a defined set of machine tools. The pallet design is optimal in terms of number of finished workpieces, saturation and balancing of the pallet.

The following hypothesis are valid:

- Pallet shape is limited to square and cubic shape
- Each pallet present a given number of fixturing faces, that are physical faces on which parts can be mounted (e.g. cube: four, square: two)
- Each fixturing face can be divided in sub-fixturing faces (Fig. 2). Each sub-fixturing faces is rectangular and is characterized by a position and two dimensions.
- Each sub-fixturing face is characterized by a workpiece patten, i.e. the number of rows and columns of workpieces.
- Only four-axis machine tools are considered

The approach is based on three different activities: setup accessibility, pallet design optimization, pallet machinability.

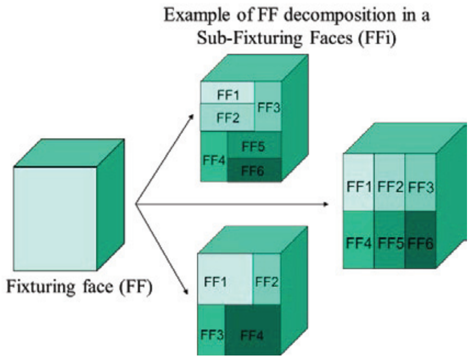

Fig. 2. Fixturing faces

4.1. Setup accessibility

Setup accessibility aims at analysing possible changes in the visibility of the TAD of the setup on the basis of the position of the workpiece in the face, the patterns of the workpieces in the same setup and the patterns of the adjacent workpieces. If the TAD of one setup operation results to be unreachable, the setup accessibility is no more granted and the solution should be discarded. The TAD accessibility is evaluated trough the kinematics study of the machine tool on which the pallet is going to be machined. The results of this activity are formalized in two matrices that represent an input for the pallet design optimization activity.

4.2. Pallet configuration

A mathematical model is developed in order to define a set of alternative pallet configurations for the machining of different part type on a preselected pallet structure. The model indexes, data and variables are presented in Table 1-3.

The idea is to maximize the number of finished part per pallet (Eq. 1), while maintaining the pallet balancing (Eq. 2) and granting the setup accessibility (Eq. 3). Two additional constraints (Eq. 4 and Eq. 5) are employed for the obtainment of alternative solutions in terms of pallet balancing and workpiece positioning. Finally, a set of constraints grant the coherence among the model data and variable. These constraints are not reported for sake of brevity.

Table 1. Model indexes.

Index	Description
W_w, $w \in \{1..NWs\}$	Workpiece type. *NWs* denotes the number of considered workpiece type.
S_s, $s \in \{1..NSs\}$	Setups. *NSs* denotes the number of considered setups.
V_v, $v \in \{1..NVFs\}$	Sub-fixturing faces. *NVFs* denotes the number of considered sub-fixturing faces.
P_p, $p \in \{1..NPs\}$	Patterns corresponding to a couple of indexes representing the number of rows and columns of the pattern $\{p^{row}, p^{column}\}$. *NPs* denotes the number of considered patterns.

R_r, $r \in \{1..Rs\}$	Number of run performed to obtain alternative solution. *Rs* denotes the number of considered runs.
E_e, $e \in \{1..NEs\}$	Elements corresponding to the quaternion of indexes $\{e^w, e^s, e^v, e^q\}$ that points to the workpice W_w in setup S_s mounted on the fixturing face V_v in patter P_p. *NEs* denotes the number of considered elements.

Table 2. Model data.

Data	Description
$WS_{w,s} \in \{0,1\}$	Workpiece setups - 1 if setup S_s refers to the workpiece W_w
$CSs_{s1,s2} \in \{0,1\}$	Combined setups - 1 if S_{s1} and S_{s2} refers to the same workpiece W_w
$AP_{w,s,v,p} \in \{0,1\}$	Available Patterns - 1 if the workpiece W_w in setup S_s can be mounted on the fixturing face V_v with pattern P_p; *0* otherwise.
$CEs_{e1,e2} \in \{0,1\}$	Combined Elements - if the selection of the element E_{e1} and the contemporary selection of the element E_{e2} is not possible due to coexistence constraints of the elements or to a limitation of the accessibility of the MWS characterizing the elements
$RP_{r,w,s,v,q}$	Vector of variables $R_{w,s,v,q}$ for the storage of the solutions already found
AltBal	0 if alternative solutions in terms of pallet balancing are requested; 1 otherwise
AltDisp	0 if alternative solutions in terms of workpiece disposition on the pallet are requested; 1 otherwise
H	High-value constant

Table 3. Model variables.

Variable	Description
$R_{w,s,v,q} \in \{0,1\}$	Results – Equal to 1 if sub-fixturing face V_v mounts pattern P_p of workpiece W_w in setup S_s; 0 otherwise

$$\text{Maximize} \quad \sum_w \left(\frac{\sum_{s,v,p} R_{w,s,v,p} P_p^{row} P_p^{column}}{\sum_s WS_{w,s}} \right) \tag{1}$$

Subject to

$$\left(\sum_{v,p} R_{w,s1,v,p} P_p^{row} P_p^{column} - \sum_{v,p} R_{w,s2,v,p} P_p^{row} P_p^{column} \right) \quad \forall s1, s2, w \tag{2}$$
$$CSs_{s1,s2} AP_{w,s1,v,p} AP_{w,s2,v,p} = 0$$

$$\left(R_{w_{e1},s_{e1},v_{e1},p_{e1}} + R_{w_{e2},s_{e2},v_{e2},p_{e2}} \right) CEs_{e1,e2} \le 1 \quad \forall e1, e2 \tag{3}$$

$$\left(\sum_{s,v,p} w \cdot RP_{r,w,s,v,p} - \sum_{s,v,p} w \cdot R_{w,s,v,p} \right) + AltBal \cdot H \ne 0 \quad \forall r, w \tag{4}$$

$$\sum_{w,s,v,p} s \cdot v \cdot RP_{r,w,s,v,p} - \sum_{w,s,v,p} s \cdot v \cdot R_{w,s,v,p} + AltDisp \cdot H \ne 0 \quad \forall r \tag{5}$$

4.3. Pallet machinability

The pallet machinability on a set of machine tools is addressed. Since no specific information in relation to the machining operations is known (e.g. torque, required power), the check will be limited to the dimensions of the configured pallet in relation to the working cube of the considered machine tools. The time needed to completely machine a pallet on the set of selected machine tools is given. This time takes into account the cutting time and the air time. Air time is evaluated identifying an operation sequence that minimizes the number of tool changes and the number of table rotations.

5. Pallet inspection

Pallet inspection stands in the measurement of the pallet, its digitalization and comparison with a reference model. The output will be the validation of the physical pallet and, if necessary, a list of possible errors.

5.1. Pallet measuring

Among vision systems technologies, e.g. structured light 3D scanner, time-of-flight scanners, laser scanner was selected for pallet digitalization due to its capability to work in dirty and noisy environments like FMSs. The system was provided with an ad-hoc-developed automatic calibration procedure. The employment of this procedure avoid manual or semi-automatic inefficient and time-consuming activities of high-skilled operators. Specifically, two correspondent sets of points can be defined: *psi ϵ {1..NPO}* - remarkable points in the scanner coordinate frame; *psi ϵ {1..NPO}* - remarkable points in the model coordinate frame. NPs denotes the number of considered points.
The relationship between the two sets of points is as follows:

$$pb_i = \overline{R} \cdot ps_i + \overline{T} + \overline{V_i} \tag{6}$$

where *R* is orthonormal rotation matrix, *T* is a translation vector and V_i is the “noise” vector. The optimal solution for *[R, T]* transformation allows the mapping of point set $\{ps_i\}$ onto $\{pb_i\}$ and the scanning point back-projection onto the model coordinate system. The solution requires a least squares error minimization criterion given by:

$$\Sigma^2 = \sum \left\| pb_i - \overline{R} \cdot ps_i - \overline{T} \right\|^2 \tag{7}$$

5.2. Pallet check

The verification of the real pallet configuration with respect to the planned one requires the comparison of the acquired point cloud with the stored ideal configuration, which specifies the correct positions and shapes of all the elements mounted in the pallet.

Therefore, the comparison corresponds to the matching problem of the acquired point cloud to the reference nominal geometry. Since the correctness of the mounted pallet at each setup has to be identified, the approach has to deal with different types of geometrical representation. Only the shape model of the final product is created and represented in CAD systems, e.g. in terms of NURBS, canonical surfaces (planes and cylinders) and splines. Shape models of the product at intermediate setup can be achieved by manufacturing process simulations in terms of polygonal models. Although such approximate models are not suitable for many tasks in CAD/CAM systems, polygonal meshes or point clouds can be derived from any CAD representation. Therefore, polygonal meshes have been selected as reference representation of the ideal pallet configuration and are generated from the CAD model saved as stl files.

To avoid false mismatches between the acquired and the ideal geometry of the configured pallet, it is necessary that the ideal representation contains only the model part that can be actually acquired by the laser scanner. Thus, a simulation of the laser scanner behavior is performed and corresponds to the detection of all the mesh elements, M_{LS}, which are simultaneously visible by the camera and the laser.

These mesh elements are obtained by computing the visible elements from the laser on the set of the submesh, M_C, visible from the camera point of view. This corresponds to the specification of the viewing frustum used in 3D computer graphics, i.e. the region of the space in the modelled world that may appear on the screen from a specific point of view [18]. The point of view of the viewing frustum corresponds to the camera position first, and then to laser position (Fig. 3). In the first case, the planes of the viewing frustum are obtained considering the angle of the optical cone. Similarly, for the laser the vertical and horizontal fan angles are considered. The open-source, freely available software system for 3D computer graphic VTK (Visualization Toolkit) [19] has been selected for the detecting the visible elements.

To limit noise in the matching, critical elements almost parallel to the view direction are removed. Thus, triangles whose normal forms an angle between [-50°, 50°] with the laser/camera ray are discarded.

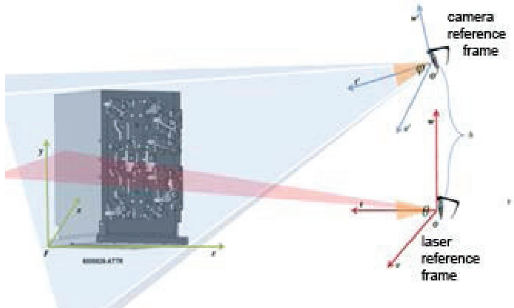

Fig. 3: laser scanner simulation

Once the CAD point cloud is available, the comparison of meaningful zones, a priori specified by the user, between these mesh patches and the scanned cloud is performed. The procedure is based on the evaluation for each zone of the minimum square error as follows: (i) for each point, acquired of three closest CAD points are identified; (ii) for each group of three points, the plane equation is evaluated; (iii) the distance between reference acquired points and planes is computed; (iv) the minimum square error based on all distances extracted is calculated.

6. Industrial case

The approach was tested on an industrial case provided by a company operating in the electrical and railway fields and producing thousands of part types, the majority of which is subject to high fluctuation of the demand. Thus, pallets are periodically reconfigured leading to the need of an automatic methodology both for the design and inspection of the pallets.

Two different part type, hereafter indicated as part type 1 (W1) and part type 2 (W2), were considered. These part types belong to the same family. They present 42 and 34 MWSs, 3 TADs in the workpiece reference system (W1 – TAD1, TAD 2, TAD3; W2 – TAD1, TAD 2, TAD3) and 3 setups each (W1 - S1, S2, S3; W2 – S4, S5, S6). The pallet design proposed by the company for the simultaneously machining of W1 and W2 is depicted in Fig. 4.

Considering the same fixture employed in the industrial case, pallet design approach leads to the obtainment of 74 alternative solutions. Among these solutions, the industrial design was found. The proposed solutions differ in terms of both balancing and positioning of the parts. For instances, solution #1 is characterized by the machining of 1 W1 and 3 W2, while solution #70 presents 2 W1 and 2 W2 (Fig. 5). All the provided solutions grant the setup accessibility. The best pallet design will be selected taking into account the demand and system loading.

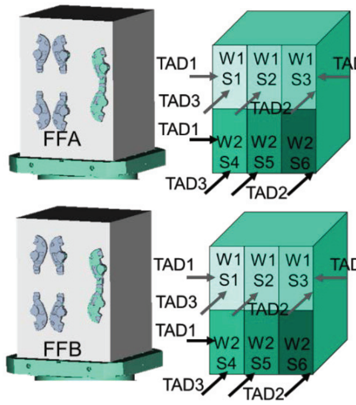

Fig. 4. Industrial solution

The machinability of all the generated pallet design has been tested on the set of machine tools composed by MCM Clock 600, NCCORREA Magna 3000 and THC Extreme 800. All the generated pallet designs result to be feasible since they fit the working cube of the machine tool. In Table 4, the approximated time for the machining of solution #1 and #70 by the set of considered machine tools is presented. For each considered machine tool, solution #1 requires a more elevated time than solution #70 since cutting time of W2 is 26% greater than cutting time of W1. Moreover, MCM and THC present equal machining times since the speed and acceleration of their axes are similar.

In order to test the pallet inspection, the pallet design corresponding to the industrial solution was considered. The CAD mesh, obtained as depicted in Section 5, was compared with the 3 scanned mesh representing 3 different situations: (i) pallet well mounted and gripping device well clamped (Fig. 6); (ii) pallet with same gripping device not well clamped; (iii) pallet without an element. The results presented in Table 5 confirm that the methodology is able to identify errors occurred during the pallet mounting.

Table 4. Pallet machining time.

	MCM	NCCORREA	THC
Sol #1	3639.19 [s]	3733.00 [s]	3639.19 [s]
Sol #70	3398.13 [s]	3509.00 [s]	3398.13 [s]

Table 5. Test results.

Pallet	Error max [mm]	Error mean [mm]	Error min [mm]
No mounting error	0.2837	0.0863	0.0254
With gripping error	1.3659	0.6347	0.0272
With element error	42.9871	10.3657	0.0231

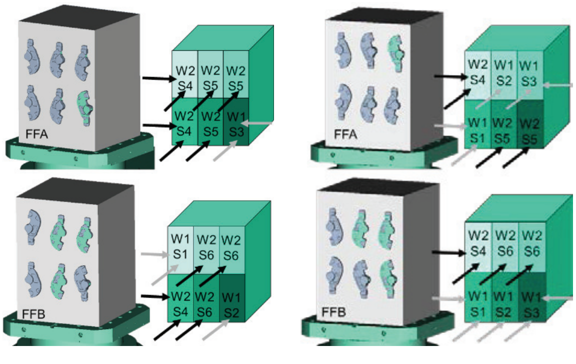

Fig. 5. Example of pallet designs. (a) Solution #1; (b) Solution #70

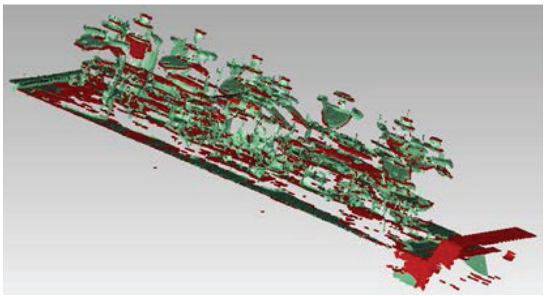

Fig. 6. Point cloud of pallet from scan (red) and ideal mesh (green).

7. Conclusions and future work

The proposed approach represents an extension of the network part program - NPP. A pallet design model for multi-part types was described together with a procedure for pallet inspection. The approach applicability and usefulness were demonstrated through the implementation on a real case.

In comparison to the state of the art, the approach proposed for the pallet design concerns the machining of different part-types. Future work will consist in the relaxation of the hypothesis on which the model currently stands (Section 4). Moreover, the paper could be extended by taking into account the fixture design problem [21].

From the point of view of the inspection method, major advantages concern the use of relatively low cost system generally applicable and of a fast comparison procedure. Nevertheless, some limitations exist related to its capability to identify the exact type of inconsistency of the actual pallet configuration. To better distinguish the occurred errors, future work will consider the use of additional shape features, as those presented in [20], for the matching of the ideal with the acquired configurations.

Furthermore, the methods presented in this paper will be integrated in an ontology-based platform in a similar fashion as shown in [22]. The goal is to enhance the interoperability with both manufacturing system design and performance evaluation tools [23].

Acknowledgements

The research has been partially funded by the Italian Flagship project FdF-SP2-T2.1 ‘Pro2Evo: Product and Process Co-Evolution Management via Modular Pallet configuration’.

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